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The orbital period of V458 Vulpeculae, a post double common-envelope nova

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ABSTRACT

We present time-resolved optical spectroscopy of V458 Vulpeculae (Nova Vul 2007 No. 1) spread over a period of 15 months starting 301 days after its discovery. Our data reveal radial velocity variations in the He II $\lambda 5412$ and He II $\lambda 4686$ emission lines. A period analysis of the radial velocity curves resulted in a period of 98.09647 ± 0.00025 min (0.06812255 ± 0.0000017 d) which we identify with the orbital period of the binary system. V458 Vul is therefore the planetary nebula central binary star with the shortest period known. We explore the possibility of the system being composed of a relatively massive white dwarf ($M_1 \gtrsim 1.0 M_\odot$) accreting matter from a post-asymptotic giant branch star which produced the planetary nebula observed. In this scenario, the central binary system therefore underwent two common-envelope episodes. A combination of previous photoionisation modelling of the nebular spectra, post-asymptotic giant branch evolutionary tracks and the orbital period favour a mass of $M_2 \sim 0.6 M_\odot$ for the donor star. Therefore, the total mass of the system may exceed the Chandrasekhar mass, which makes V458 Vul a Type Ia supernova progenitor candidate.

Key words: accretion, accretion discs – binaries: close – stars: individual: V458 Vul – novae, cataclysmic variables

1 INTRODUCTION

V458 Vul (Nova Vul 2007 No. 1) was discovered at 9.5 magnitude on 2007 August 8 (Nakano et al. 2007), shortly before peaking at $V = 8.1$. It is classified as a fast nova on the basis of its rapid three-magnitude brightness fall from maximum within 21 days, indicative of a relatively massive ($\sim 1 M_\odot$) white dwarf. In our first paper (Wesson et al. 2008, hereafter W08) we reported the discovery of a wasp-

waisted planetary nebula surrounding the $r' = 18.34$ nova progenitor, and speculated about the possibility of the central binary star in V458 Vul being composed of a white dwarf and a post-asymptotic giant branch (post-AGB) star which formed the planetary nebula. However, the lack of an accurate orbital period prevented any further discussion. In addition, Goranskij et al. (2008) had suggested a tentative orbital period of 0.59 d from photometric light curves. In an attempt to measure a precise orbital period we started a time-resolved spectroscopy campaign searching for the or-

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Table 1. Log of the observations.

Date	Telescope/ Instrument	Grating	Slit width (arcsec)	Wavelength range	Exp. time (s)	Time coverage (h)	Dispersion (\AA pix^{-1})	Resolution (\AA)
2008 Jun 04	INT/IDS	R300V	1.2	$\lambda\lambda 3320\text{--}8400$	300	5.7	1.9	5.0
2008 Jun 25	INT/IDS	R632V	1.5	$\lambda\lambda 4405\text{--}7150$	300	3.3	0.9	2.8
2008 Jul 04	WHT/ISIS	R1200B	1.0	$\lambda\lambda 4929\text{--}5644$	300	7.4	0.2	0.7
2008 Oct 13	INT/IDS	R300V	1.0	$\lambda\lambda 3288\text{--}8870$	300	3.6	1.9	4.4
2008 Oct 14	INT/IDS	R300V	1.0	$\lambda\lambda 3294\text{--}8400$	300	3.6	1.9	4.4
2008 Nov 11	WHT/ISIS	R600B	1.0	$\lambda\lambda 3584\text{--}5117$	300	3.7	0.9	1.5
2009 May 25	INT/IDS	R632V	1.2	$\lambda\lambda 4500\text{--}6830$	600	3.2	0.9	2.4
2009 Jul 21	WHT/ISIS (QUCAM3)	R600B	1.0	$\lambda\lambda 4500\text{--}4930$	30	4.4	0.4	1.5
2009 Aug 31	INT/IDS	R632V	1.2	$\lambda\lambda 4500\text{--}6830$	600, 800	4.0	0.9	2.4

Notes on instrumentation: INT/IDS: 2.5-m Isaac Newton Telescope at Roque de los Muchachos Observatory (ORM), using the Intermediate Dispersion Spectrograph with a $2k \times 4k$ pixel E2V CCD; WHT/ISIS: 4.2-m William Herschel Telescope (WHT) at ORM, using the Intermediate dispersion Spectrograph and Imaging System with its $2k \times 4k$ pixel E2V CCD.

bital signature in the radial velocities of the emission lines. The results of this campaign are presented in this letter.

2 OBSERVATIONS AND DATA REDUCTION

The spectroscopic data were obtained with the Intermediate Dispersion Spectrograph (IDS) on the 2.5-m Isaac Newton Telescope (INT) and the Intermediate dispersion Spectrograph and Imaging System (ISIS) on the 4.2-m William Herschel Telescope (WHT), both on La Palma. The log of spectroscopic observations can be found in Table 1.

The spectra were reduced using the standard IRAF longslit packages. The one-dimensional spectra were then extracted using the optimal extraction algorithm of Horne (1986). Wavelength calibration was performed in MOLLY¹ by means of arc lamp spectra frequently taken to guarantee an accurate wavelength solution. The spectra were then flux calibrated and de-reddened using $E(B - V) = 0.63$ (W08) using MOLLY. For the fast spectroscopy QUCAM3 data we averaged in blocks of 10 spectra in order to achieve a proper signal-to-noise ratio for radial velocity measurement.

3 EARLY RADIAL VELOCITY VARIABILITY

The average optical spectrum of V458 Vul taken on 2008 June 4 (day 301 after the nova explosion) is shown in Fig. 1. It is mainly dominated by emission lines of [Ne V], [Fe VII], He II, and the hydrogen Balmer series. The round-topped profile of the He II $\lambda 5412$ line attracted our attention during a first visual inspection of the line shapes. After normalising the adjacent continuum, we cross-correlated the individual He II $\lambda 5412$ profiles with a Gaussian template with a full-width at half-maximum (FWHM) of 400 km s^{-1} . We found the radial velocity to vary between ~ -200 and $\sim 200 \text{ km s}^{-1}$. This radial velocity variation indicated that at least one of the components of the He II $\lambda 5412$ emission forms in a

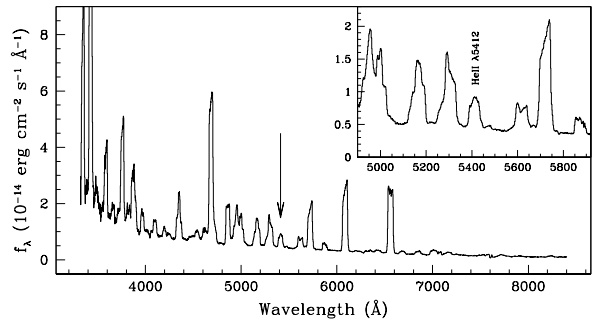


Figure 1. Average of 15 spectra taken with INT/IDS on 2008 June 4 (301 days after the nova explosion). The arrow points to the He II $\lambda 5412$ emission line, which showed significant radial velocity shifts while the line emission was still dominated by the nova shell.

binary system at the core of the planetary nebula. This finding prompted further time-resolved spectroscopy (see Table 1) in an attempt to measure its orbital period.

4 THE ORBITAL PERIOD OF V458 VUL

4.1 Period analysis of the radial velocity curves

We obtained radial velocity curves of the He II $\lambda 5412$ emission line on 2008 June 25, July 4, October 13, and October 14. By that time no He II $\lambda 4686$ radial velocity variation was detected. This wasn't unexpected since the He II $\lambda 4686$ line has to thin out (i.e. shed some nova ejecta emission) before it starts to present the same phenomenon as the weak, optically-thin transition of the He II $\lambda 5412$ line. The He II $\lambda 4686$ emission showed a clear modulation by November 2008. Therefore, we also measured radial velocities of this much brighter line on 2008 November 11, and 2009 May 25, July 21, and August 31. Before measuring the velocities, the spectra were first re-binned to constant velocity increments and continuum-normalised. Radial velocities were then measured by cross-correlation with a single Gaussian template. The FWHM of the template used for a given

¹ <http://www.warwick.ac.uk/go/trmarsh/software>

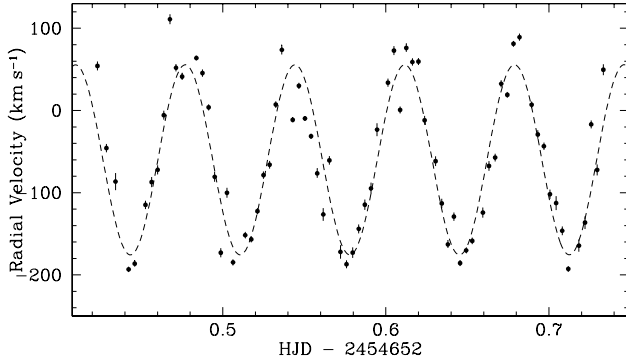


Figure 2. He II $\lambda 5412$ radial velocity curve obtained with WHT/ISIS on 2008 July 4. The velocities were measured by cross-correlating the individual profiles with a Gaussian template of $\text{FWHM} = 400 \text{ km s}^{-1}$. A sine fit to the data results in a period of $0.06731 \pm 0.00038 \text{ d}$ and an amplitude of $115 \pm 5 \text{ km s}^{-1}$.

night was adjusted so that the cleanest radial velocity curve was obtained, but it always varied between 400 and 1200 km s^{-1} . The radial velocity curve of V458 Vul exhibits a quasi-sinusoidal modulation. The longest observation (over 7 h, 2008 July 4) covers over five cycles, and a sine fit to these data results in a period of $0.06731 \pm 0.00038 \text{ d}$ and an amplitude of $115 \pm 5 \text{ km s}^{-1}$ (Fig. 2).

In order to refine the orbital period of V458 Vul we subjected the radial velocity measurements to a period analysis using Schwarzenberg-Czerny’s (Schwarzenberg-Czerny 1996) variation of the analysis-of-variance method implemented as *ORT* in *MIDAS*, which fits periodic orthogonal polynomials to the phase-folded data. The periodogram calculated from the 2008 July 4 data (Fig. 3, top panel) exhibits a strong peak at 14.86 d^{-1} , consistent with the result from the sine fit mentioned above. Next, we analysed the He II $\lambda 5412$ radial velocities, which represent about 2/3 of all our radial velocity data and were obtained with relatively frequent sampling between June and October 2008. The resulting periodogram (Fig. 3, middle panel) contains the strongest peak at 14.68 d^{-1} , and the observed alias pattern is consistent with the window function resulting from our temporal sampling. Finally, we analysed the combined He II $\lambda 5412$ and He II $\lambda 4686$ data, which extend the total baseline spanned by our observations to 430 d. The resulting periodogram is characterised by a narrow spike at 14.68 d^{-1} , consistent with period determinations of the smaller radial velocity subsets. No signal at the period claimed by Goranskij et al. was found. A sine fit to the whole data set results in $P = 0.06812255 \pm 0.00000017 \text{ d}$ or $98.09647 \pm 0.00025 \text{ min}$. The He II $\lambda 5412$ and He II $\lambda 4686$ velocities folded on the orbital period are shown in Fig. 3 (bottom panel). Our results show that the period is coherent for 6341 cycles, suggesting it is a fixed clock in the system. We therefore identify this period with the orbital period of the binary progenitor of nova V458 Vul, which makes it the central binary system of a planetary nebula with the shortest orbital period (see e.g. de Marco 2009, for a list).

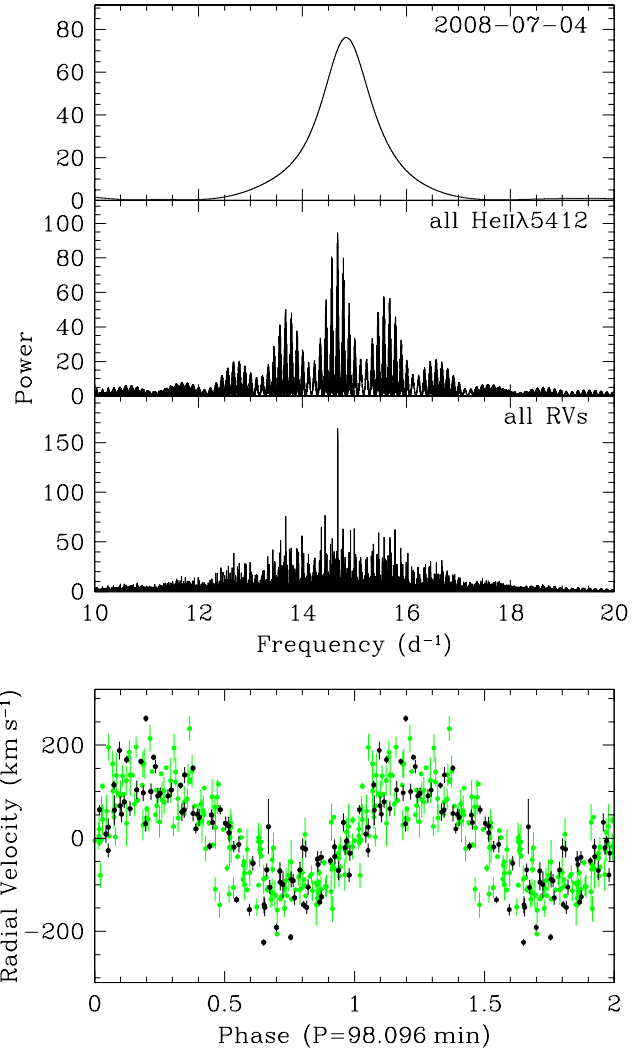


Figure 3. *Top three panels:* ORT periodograms of the single longest observation (see Fig. 2), of all the He II $\lambda 5412$ radial velocities obtained between June and October 2008, and of all the He II $\lambda 5412$ and He II $\lambda 4686$ radial velocities obtained up to September 2009. *Bottom panel:* Mean-subtracted and phase-folded He II $\lambda 5412$ (green) and He II $\lambda 4686$ (black) radial velocities. The time of zero phase (blue to red crossing) is $T_0(\text{HJD}) = 2454652.52694 \pm 8 \times 10^{-5}$.

4.2 Triled spectra diagrams

The long-term evolution of the He II $\lambda 5412$ and He II $\lambda 4686$ emission lines is shown in Fig. 4. He II $\lambda 5412$ started to reveal the orbital motion of V458 Vul much earlier than He II $\lambda 4686$. By May 2009, He II $\lambda 4686$ displayed an apparent orbital signal in the form of a clear S-wave. Note that orbital phases were computed relative to the blue-to-red velocity crossing of this S-wave, which would correspond to the standard definition of the orbital phase if the S-wave originates on the donor star. The trailed spectra diagram of this line also shows high velocity wings extending up to $\sim \pm 1000 \text{ km s}^{-1}$. This might indicate the presence of another emission component apart from the dominant S-wave.

A deeper look at the May 2009 spectra revealed narrow emission components bluewards of He II $\lambda 4686$ (see

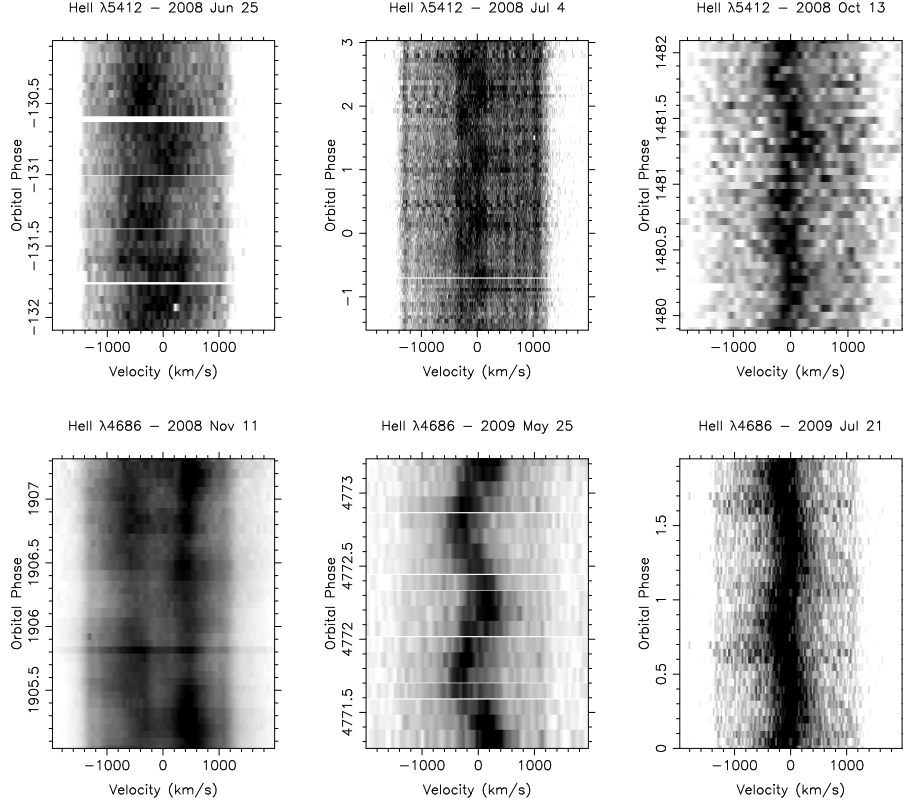


Figure 4. Evolution of the He II emission lines. *Top panel:* He II $\lambda 5412$ trailed spectra diagrams. *Bottom panel:* He II $\lambda 4686$ trailed spectra diagrams. Black represents emission. No phase binning has been applied, with the exception of the QUCAM data taken on 2009 July 21. In this last diagram a full cycle has been repeated for clarity.

Fig. 5). The first two, counting from He II $\lambda 4686$, lie at rest wavelengths of ~ 4640.6 and ~ 4634.2 Å and have $\text{FWHM} \sim 230 \text{ km s}^{-1}$. These narrow lines, reminiscent of the radiation-driven Bowen fluorescence lines used to probe the motion of the irradiated donor star in X-ray binaries (e.g. Steeghs & Casares 2002), are in phase with the He II $\lambda 4686$ S-wave and their radial velocity amplitudes are comparable within what are necessarily substantial error bars. This lends further support to place these S-waves on the irradiated donor star. In V458 Vul, the white dwarf producing the nova explosion can provide the EUV radiation needed to trigger the process. In fact, two N III transitions take place at 4640.64 and 4634.13 Å, very close to the observed lines. The other two emissions are likely the N V doublet lines at 4603.74 and 4619.97 Å. If all these narrow lines originate on the irradiated donor star, our adopted phase convention is the correct one.

5 DISCUSSION AND CONCLUSIONS

In W08 we presented photoionisation modelling of the nebular spectra obtained before the nova explosion ionised the planetary nebula. This implied an ionising source with effective temperature $T_{\text{eff}} \approx 90000 \text{ K}$, luminosity $L_{\text{bol}} \approx 3000 L_{\odot}$ and radius $R \approx 0.23 R_{\odot}$. In the same paper we showed that, based on the hydrogen-burning evolutionary tracks of Vassiliadis & Wood (1994), this requires a core mass of $0.58 M_{\odot}$ and an age since leaving the AGB consistent with our estimated nebular expansion age of 14000 years.

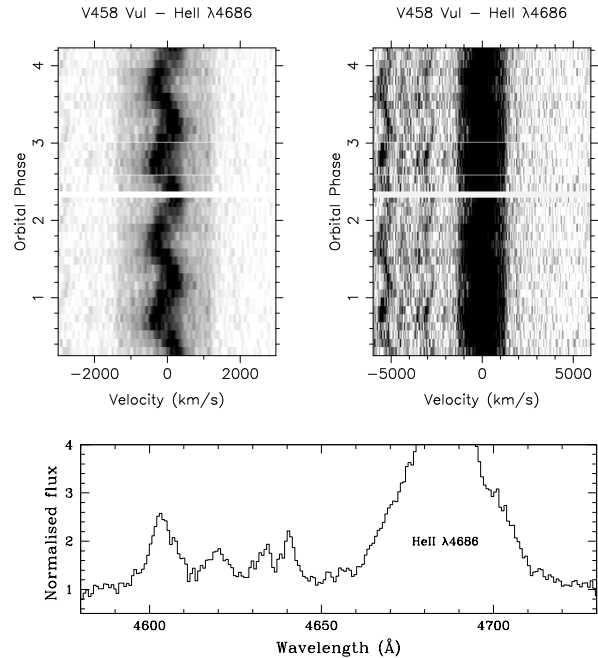


Figure 5. *Top:* He II $\lambda 4686$ trailed spectra diagram of the May 2009 run after averaging into 40 phase bins. Contrast has been adjusted to highlight the main S-wave (*left*) and the narrow components bluewards of He II $\lambda 4686$ (*right*). Black represents emission and a full cycle has been repeated for clarity. *Bottom:* Doppler-corrected average spectrum of the May 2009 run.

The question now is: which of the two stars is the progenitor of the planetary nebula? The short orbital period of V458 Vul and the age of its planetary nebula may seem at odds if one assumes the system is actually a cataclysmic variable (CV) which evolved from a much longer orbital period by losing angular momentum due to magnetic wind braking (Verbunt & Zwaan 1981; Rappaport et al. 1983) and radiation of gravitational energy (Faulkner 1971; Paczyński & Sienkiewicz 1981). The time it takes a CV to evolve down to an orbital period of 98.1 min is of the order of a Gyr (Rappaport et al. 1983). However, it is possible to get a short-period, *normal* CV within a common envelope (e.g. the case of the young pre-CV SDSS J005245.11–005337.2 in Rebassa-Mansergas et al. 2008), but producing a nova event in this scenario within 14000 years is very unlikely.

This strengthens the possibility, as suggested by W08, of the donor star in V458 Vul being actually an evolved star, i.e. a post-AGB star. In such a case, the planetary nebula of V458 Vul may have been ejected by the donor star instead of the accreting white dwarf after a second common-envelope phase. As mentioned above, the post-AGB donor would therefore have a mass of $0.58 M_{\odot}$.

Theoretical nova models (e.g. Prialnik & Kovetz 1995; Yaron et al. 2005) agree that a minimum white dwarf mass $M_1 \sim 1 M_{\odot}$ is required to trigger the thermonuclear runaway in fast novae like V458 Vul. Observations, although scarce, point to a similar value (Ritter & Kolb 2003). Hence, the total mass of V458 Vul may well be $\gtrsim 1.6 M_{\odot}$, above the critical Chandrasekhar mass, indicating that it may become a Type Ia supernova if the white dwarf manages to accumulate mass in the presence of nova eruptions.

Several other systems have been claimed as Type Ia supernova progenitors. The subdwarf-B+white dwarf binary KPD 1930+2752 is among the best candidates, but its total mass is very close to the critical mass (Maxted et al. 2000; Ergma et al. 2001; Geier et al. 2007). The first He nova, V445 Puppis, may contain a binary system composed of a massive white dwarf accreting from a helium star companion (Woudt et al. 2009). The 3.9-h central binary star of planetary nebula PNG135.9+55.9 (SBS 1150+599A) has also been put forward (Tovmassian et al. 2010). In this case, a post-AGB star and, presumably, a compact companion also amount to a mass just close to the Chandrasekhar limit.

An obvious objection to our scenario is the fact that the post-AGB donor star would have to fill its Roche lobe in order to sustain mass transfer while it is still contracting. A star filling its Roche lobe must obey an orbital period-mean density law, so we used the evolutionary tracks of Blöcker (1995) in an attempt to find stellar parameters which fit both the 98-min orbit of V458 Vul and the results of our photoionisation model. We find that a star with an initial and final mass of $3 M_{\odot}$ and $0.625 M_{\odot}$, respectively, on a helium burning track at 14000 yr, provides almost perfectly the measured effective temperature, luminosity and radius of the ionising source. However, steady mass transfer (i.e. contact with the Roche lobe) depends on the timescales over which orbital angular momentum is lost during the second common-envelope phase and contraction of the post-AGB donor star take place. Both processes have very short and similar timescales (of a few thousands years), making the situation very difficult to quantify. Only further spectroscopic

search for spectral lines from both components of the binary system may shed more light onto its dynamics and nature.

In conclusion, we have solidly measured an orbital period of 98.09647 ± 0.00025 min for V458 Vul. A plausible scenario explaining V458 Vul is that of a double common-envelope binary system composed of a $M_1 \gtrsim 1 M_{\odot}$ white dwarf (the accretor) and a $M_2 \sim 0.6 M_{\odot}$, post-AGB star (the donor) which expelled the planetary nebula 14000 yr ago. The total mass of the system may therefore well exceed the Chandrasekhar mass which, in addition to its close orbit, makes V458 Vul a Type Ia supernova progenitor candidate.

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